

DISTRIBUTED VERSUS TACHOCLINE DYNAMOS

Axel Brandenburg

Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

ABSTRACT

Arguments are presented in favor of the idea that the solar dynamo may operate not just at the bottom of the convection zone, i.e. in the tachocline, but it may operate in a more distributed fashion in the entire convection zone. The near-surface shear layer is likely to play an important role in this scenario.

Key words: Magnetohydrodynamics (MHD) – turbulence – Sun: magnetic fields.

1. RECENT DEVELOPMENTS

The issue of the location of the solar dynamo has been discussed and reviewed in a number of recent papers. Over the past 25 years a general consensus has been developing to place the solar dynamo at the bottom of the convection zone or even beneath it in the overshoot layer. This location also coincides with the tachocline, where the latitudinal differential rotation in the convection zone turns into rigid rotation in the radiative interior. A number of arguments in favor and against both distributed and overshoot dynamos have been collected in Brandenburg (2005). Which of the two scenarios is more viable cannot yet be decided conclusively until more realistic turbulence simulations of the solar dynamo become available.

From a dynamo-theoretic point of view it appears rather difficult to produce ~ 100 kG fields that are required in the standard scenario of an overshoot dynamo (D'Silva & Choudhuri 1993, Schüssler et al. 1994, Caligari, Moreno-Insertis, & Schüssler 1995). Looking at a mixing length model of the solar convection zone, the equipartition field strength at the bottom of the convection zone is less than 1 kG, so the dynamo would need to produce a field in excess of a hundred times the equipartition value; see Table 1, where we have used data from stellar envelope models of Spruit (1974). Also, the idea of flux tubes ascending without disrupting through 20 pressure scale heights all the way from the bottom of the convection zones to the top seems nearly impossible.

By contrast, distributed dynamos operating in the entire convection zone would be expected to have sub-equipartition field strengths of around 300 G for the mean field. An important ingredient is the presence of shear; recent simulations (Brandenburg 2005) indicated that not even helicity is essential for producing large scale fields. Occasionally, such simulations produce what looks like bi-polar regions. So, the typical picture of Ω -shaped loops tied to the bottom of the convection zone (Parker 1979) may not be quite accurate, and the whole sunspot phenomenon may be rather more shallow than suggested by the standard picture. Examples of synthetically produced magnetograms are shown in Fig. 1.

In the present scenario the peak fields that emerge at the surface are thought to be the result of local concentrations. According to work by Kitchatinov & Mazur (2000), sunspots are actually the result of an instability of the mean-field equations of radiation magnetohydrodynamics, possibly assisted by negative turbulent magnetic pressure effects (Kleeorin, Mond, & Rogachevskii 1996). These ideas are in some ways similar to the convective collapse of magnetic fibrils (Zwaan 1978, Spruit & Zweibel 1979).

The usual argument against dynamos working in the convection zone proper is that magnetic buoyancy would bring the field to the surface on too short a time scale (Moreno-Insertis 1983). Indeed, buoyant loss of magnetic fields were anticipated when the first compressible simulations of convective dynamo action came out (Nordlund et al. 1992, Brandenburg et al. 1996). The lack of evidence for buoyant loss of magnetic field was explained by the stronger effect of turbulent downward pumping. This idea has recently been studied in much more detail (Tobias et al. 1998, 2001, Dorch & Nordlund 2001, Ossendrijver et al. 2002, Ziegler & Rüdiger 2003).

A more complete list of arguments both in favor and against distributed dynamos versus tachocline dynamos is given in Table 2. For a more complete discussion of the various points see Brandenburg (2005).

An important aspect that requires some appreciation is simply the fact that mean (toroidally averaged) fields close to equipartition strength can actually be produced.

Table 1. Solar mixing length model of Spruit (1974). The equipartition field strength obeys $B_{\text{eq}}^2/4\pi = \rho u_{\text{rms}}^2$.

z [Mm]	H_p [Mm]	u_{rms} [m/s]	τ [d]	ν_t [cm ² /s]	$2\Omega_0\tau$	B_{eq} [G]
24	8	70	1.3	1.5×10^{12}	0.6	1600
39	13	56	2.8	2.0×10^{12}	1.3	2000
155	48	25	22	3.2×10^{12}	10	3100
198	56	4	157	0.6×10^{12}	70	650

Table 2. Summary of arguments for and against tachocline and distributed dynamos, some of which are discussed in the text. [Adapted from Brandenburg (2005).]

arguments	tachocline dynamos	distributed/near-surface dynamos
in favor	flux storage turbulent distortions weak correct butterfly diagram with mer. circ. size of active regions naturally explained	negative surface shear yields equatorward migration correct phase relation strong surface shear at latitudes where the spots are $\max(\Omega)/2\pi = 473$ nHz agrees with Ω (youngest spots) active zones move with $\Omega(0.95)$ 11 yr variation of Ω seen in the outer 70 Mm even fully convective stars have dynamos
against	100 kG field hard to explain flux tube integrity during ascent too many flux belts in latitude maximum radial shear at the poles no radial shear where sunspots emerge quadrupolar parity preferred wrong phase relation 1.3 yr variation of Ω at base of CZ coherent mer. circ. pattern required	strong turbulent distortions rapid buoyant losses too many flux belts if dynamo only in shear layer not enough time for shear to act long term stability of active regions profile of Ω (youngest) by 4 nHz above $\Omega(0.95)$ possible anisotropies in supergranulation

This is an important result because there is a long history of arguments about the very possibility of producing large scale magnetic fields by the famous α effect, starting with the work of Vainshtein & Cattaneo (1992) and Cattaneo & Hughes (1996). Again, this is not the place to attempt reviewing the vast amount of literature that has emerged over the past few years. An excellent review has been given by Ossendrijver (2003). For yet more recent aspects see the review by Brandenburg & Subramanian (2005a).

At the heart of the problem with the α effect is the fact that this and a few other related effects produce large scale magnetic helicity. On the other hand, the total magnetic helicity obeys a conservation law. However, since the *total* magnetic helicity is the sum of large scale magnetic helicity and small scale helicity, the production large scale magnetic helicity of one sign must imply the production of a similar amount of small scale helicity of the opposite sign. It is this small scale helicity of the opposite sign that acts are to quench and suppress the original α effect (Pouquet, Frisch, & Léorat 1976). In the absence of magnetic helicity fluxes, this leads to a resistively controlled slow-down toward the final saturation of the dynamo (Brandenburg 2001). This behavior is now well reproduced in the framework of the dynamical quenching model (Field & Blackman 2002, Blackman & Brandenburg 2002, Subramanian 2002).

A possible way out of this was suggested first by Black-

man & Field (2000a,b) who proposed that small scale magnetic helicity could leave the sun through the surface so as to allow the dynamo to saturate unimpededly; see also Kleeorin et al. (2000, 2002, 2003) for similar work on the galactic dynamo. However, this does not happen just automatically; what is required is an active driving of magnetic helicity flux within the domain toward the boundaries. One such flux was identified by Vishniac & Cho (2001). Their flux works only in the presence of shear; see Subramanian & Brandenburg (2004, 2005), and Brandenburg & Subramanian (2005b). Another important flux would be due to simple advection; see Shukurov et al. (2005). The way the sun could dispose of its excess small scale magnetic helicity might be through coronal mass ejections (Blackman & Brandenburg 2003). Figure 2 shows the dramatic difference between simulations with and without open boundaries. This simulation does have strong shear, which is important for driving the Vishniac & Cho (2001) flux.

2. CONCLUDING REMARKS

In this short paper we have summarized just a few of the aspects that appear crucial in determining the location of the solar dynamo. As we have said in the beginning, a full account of these ideas is given in Brandenburg (2005), and have been reviewed in Brandenburg

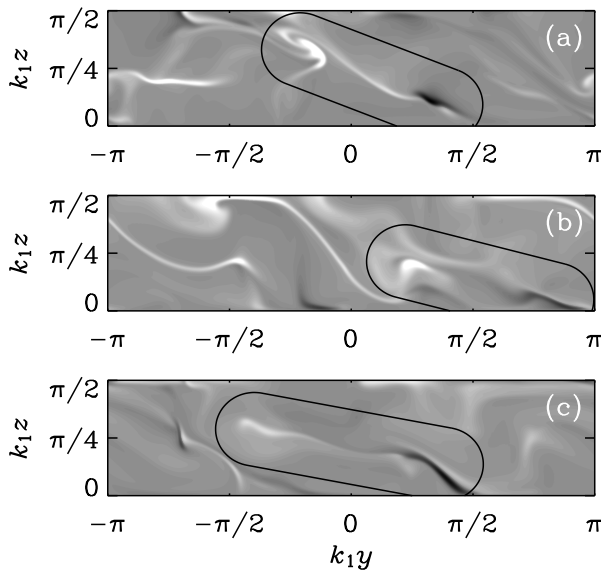


Figure 1. Magnetograms of the radial field at the outer surface on the northern hemisphere at different times. Light shades correspond to field vectors pointing out of the domain, and dark shades correspond to vectors pointing into the domain. The elongated rings highlight the positions of bipolar regions. Note the clockwise tilt relative to the y (or toroidal) direction, and the systematic sequence of polarities (white left and dark right) corresponding to $\overline{B}_y > 0$. [Adapted from Brandenburg (2005).]

(2006). The main reason is that a distributed dynamo appears quite plausible, i.e. previous problems have largely been ruled out. Furthermore, from a dynamo-theoretic viewpoint, dynamos operating only in a narrow shell at the bottom of the convection zone appear rather implausible. As far as observational evidence is concerned, one can say that the distributed dynamo scenario is at least not in conflict with observations. Moreover, as expected, the magnetic field drives cyclic variations of the toroidal flow speed (so-called torsional oscillations) with the 11 year cycle period (Howe et al. 2000a, Vorontsov et al. 2002). The amplitude of these flow variations decreases with depth, which is mainly due to the larger mass to be swung around at greater depth. However, if the dynamo really produced 100 kG fields in the overshoot layer, one would eventually expect corresponding flow variations at that depth. Such variations may currently still be below the detection limit, but what is seen are variations with a typical period of around 1.3 year at the base of the convection zone (Howe et al. 2000b).

Another aspect concerns the proper motion of sunspots: young sunspots are known to rotate faster than older ones (Tuominen 1962). This suggests that sunspots may be anchored in the layer where the angular velocity is maximum (Tuominen & Virtanen 1988, Balthasar, Schüssler, & Wöhl 1982, Nesme-Ribes, Ferreira, & Mein 1993, Pulkkinen & Tuominen 1998). The rotational velocity of very young sunspots (age less than 1.5 days) is $14.7^\circ/\text{day}$

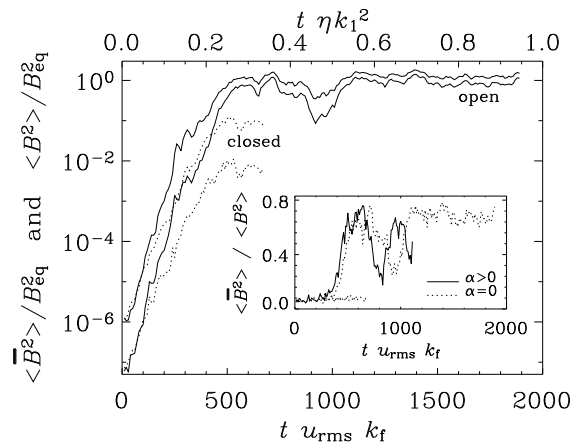


Figure 2. Evolution of the energies of the total field $\langle B^2 \rangle$ and of the mean field $\langle \overline{B}^2 \rangle$, in units of B_{eq}^2 , for runs with non-helical forcing and open or closed boundaries; see the solid and dotted lines, respectively. The inset shows a comparison of the ratio $\langle \overline{B}^2 \rangle / \langle B^2 \rangle$ for nonhelical ($\alpha = 0$) and helical ($\alpha > 0$) runs. For the nonhelical case the run with closed boundaries is also shown (dotted line near $\langle \overline{B}^2 \rangle / \langle B^2 \rangle \approx 0.07$). Note that saturation of the large scale field occurs on a dynamical time scale; the resistive time scale is given on the upper abscissa. [Adapted from Brandenburg (2005).]

at low latitudes (Pulkkinen & Tuominen 1998), corresponding to 473 nHz, which is about the largest angular velocity measured with helioseismology anywhere in the sun. This corresponds to the helioseismologically determined angular velocity at a radius $r/R = 0.95$, which is 35 Mm below the surface. Similar conclusions can be drawn from the apparent angular velocity of old and new magnetic flux at different latitudes (Benevolenskaya et al. 1999).

There is still a problem in understanding why the cycle period is 22 years, and not 3 years, which would be the natural frequency for distributed dynamos (Köhler 1973). This is in principle also a problem for overshoot dynamos and it is traditionally “solved” by postulating an overall decrease of the electromotive force. This is obviously not satisfactory. A plausible “excuse” for such an overall decrease of the electromotive force might be a partial alleviation of catastrophic quenching due to magnetic helicity fluxes, mediated by coronal mass ejections. However, at the moment there is no dynamo model taking seriously into account the magnetic helicity losses due to coronal mass ejections. However, this would be a major goal for future work.

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